Citation for published version


DOI

https://doi.org/10.1109/TASC.2018.2791515

Link to record in KAR

https://kar.kent.ac.uk/65716/

Document Version

Publisher pdf

Copyright & reuse
Content in the Kent Academic Repository is made available for research purposes. Unless otherwise stated all content is protected by copyright and in the absence of an open licence (eg Creative Commons), permissions for further reuse of content should be sought from the publisher, author or other copyright holder.

Versions of research
The version in the Kent Academic Repository may differ from the final published version. Users are advised to check http://kar.kent.ac.uk for the status of the paper. Users should always cite the published version of record.

Enquiries
For any further enquiries regarding the licence status of this document, please contact researchsupport@kent.ac.uk

If you believe this document infringes copyright then please contact the KAR admin team with the take-down information provided at http://kar.kent.ac.uk/contact.html
Can Topological Transitions be Exploited to Engineer Intrinsically Quench-Resistant Wires?

Philip Whittlesea, Jorge Quintanilla, James F. Annett, Adrian D. Hillier, and Chris Hooley

Abstract—In this paper, we investigate whether by synthesizing superconductors that are tuned to a topological, node-reconstruction transition point, we could create superconducting wires that are intrinsically resilient to quenches. Recent work shows that the exponent characterizing the temperature dependence of the specific heat of a nodal superconductor is lowered over a region of the phase diagram near topological transitions where nodal lines form or reconnect. Our idea is that the resulting enhancement of the low-temperature specific heat could have a potential application in the prevention of superconductor quenches. We perform numerical simulations of a simplified superconductor quench model. Results show that decreasing the specific heat exponent can prevent a quench from occurring and improve quench resilience, though in our simple model the effects are small. Further work will be necessary to establish the practical feasibility of this approach.

Index Terms—Energy dissipation, superconducting filaments and wires, superconducting magnets, superconducting magnetic energy storage, waste heat.

I. INTRODUCTION

QUENCHES limit the application of superconductors in magnetic field generation, energy transmission and energy storage. When a superconductor quenches, a random fluctuation leads to a phase transition of the entire material. In short, some small finite region of the superconductor can transition into its normal state, with \( T \geq T_c \), thus losing its superconducting properties. In this small normal region the superconductor suddenly has finite resistivity and will generate heat if a current is passing through it. The heat generated by this normal region transfers to the surrounding superconducting regions which can become normal as well. In turn this generates more heat until eventually the entire superconductor is heated up above \( T_c \), and it is said to have quenched. Engineering applications of superconductors already utilise a whole host of quench prevention and protection techniques, ranging from electronic detection methods to current-sharing fail-safe systems [1]–[6]. In spite of this, quenches do occur regularly; the most well-known example being that which led to the shutdown of the LHC experiment at CERN for months in 2008 [7].

Topology in condensed matter opens up a different avenue from the usual Ginzburg-Landau viewpoint. Instead of changes in symmetry the focus is on changes in topology. From this viewpoint a host of phenomena can be described, from topological insulators to Lifshitz transitions to Majorana fermions [8]–[10], none of which can be understood purely from a symmetry viewpoint. It has been proposed that topologically protected states could be usefully applied to quantum computing [11]. Here we suggest the possibility that topological transitions in superconductors could be used to make quench-resistant wires for energy transport and storage.

Unconventional superconductors can have nodal points or lines in the quasiparticle energy spectrum where the energy gap is zero [12]. A region on the Fermi surface with zero energy gap allows for arbitrarily low energy excitations. This impacts the thermodynamic properties of the system e.g. point- and line-nodes cause \( T^3 \) and \( T^2 \) specific heat dependence respectively [12], [13], rather than the exponential suppression found in conventional BCS superconductors. Recently there has been interest in anomalously-low exponents obtained at topological transitions where nodal lines cross (\( n = 1.8 \)), form (\( n = 1.5 \)) or even form and cross simultaneously (\( n = 1.4 \)) [14]. These result from the non-linear dispersion of quasiparticles near the nodal regions at the transition point.

Topological phases can occur in superconductors where different quantum ground states are identified with different topological invariants [15]. Here we are interested in the topological node-reconstruction transition [14], [16] where nodal lines on the Fermi surface form, cross or reconstruct as some tuning parameter is changed, changing the associated topological number [14], [17], [18]. In this case the associated topological number is the number of nodal lines on the Fermi surface which can only change by multiples of two.

One feature of the node-reconstruction transition is that the low temperature specific heat is enhanced, with exponents even lower than 2 or 3 [14], [18]. Furthermore, at finite temperature this effect is present over a swathe of tuning-parameter space; meaning it is not necessary to sit exactly at the transition to exploit the enhanced specific heat [14]. Here we
investigate whether by synthesising superconductors that are tuned to the topological, node-reconstruction transition point we could create superconducting wires that are intrinsically resilient to quenches.

Our idea is based on the principle that the superconductor in the node-reconstruction state can absorb more heat before increasing in temperature itself due to its enhanced specific heat. The more energy it can absorb before increasing in temperature the more resilient it should be to quenching. This “passive” approach to quench prevention is quite different to the existing approach of engineering solutions as mentioned previously. The two different approaches are entirely complementary. Materials that can be tuned to node formation/reconstruction transitions include the non-centrosymmetric superconductors Li$_2$(Pt, Pd)$_3$B [19] and the high-temperature cobalt-doped pnictides Ba(Fe$_{1-x}$T$_x$)$_2$As$_2$ (T = Co, Ni, Pd) [18], [20], [21].

II. Model

A cable-in-conduit-conductor, CICC, has a core made of superconducting wires with a copper matrix throughout. It is surrounded by some liquid coolant and enclosed with cladding.

Our starting point is the general model for a CICC, found in [6]. It consists of a collection of coupled partial differential equations: a heat equation with source terms for the wire itself; another heat equation for the cladding, both depend on the temperature of the coolant; and another set of equations describing the temperature change and fluid dynamics of the coolant itself. In order to prove our concept we use a simplified version of this model which captures the relevant physics, specifically a pair of partial differential equations describing heat flow in the superconductor and in the bath:

\[
C^*_c(T^*(x^*, t^*), T^0_c) \frac{\partial T^*(x^*, t^*)}{\partial t^*} = \frac{\partial^2 T^*(x^*, t^*)}{\partial x^2} - (T^*(x^*, t^*) - T^0_h(x^*, t^*)) + \Theta(T^*(x^*, t^*) - T^c_c)
\]

\[
\frac{\partial T^0_h(x^*, t^*)}{\partial t^*} = \beta(T^*(x^*, t^*) - T^0_h(x^*, t^*))
\]

where

\[
t_0 = \frac{\rho_s C_0 \gamma^2}{\kappa_c}
\]

\[
\beta = \frac{\rho_s C_0 A_c}{\rho_c C_h A_h}
\]

Here the subscripts $c$ and $h$ differentiate between the conductor and helium respectively. $\rho$ is the density, $\kappa$ is the thermal conductivity, $h$ is the heat transfer coefficient, $P$ is the wetted perimeter and $A$ is the cross-sectional area of the conductor, $\eta$ is the resistivity, $I$ is the current in the conductor and $\gamma$ is the Sommerfeld specific heat of the superconductor.

Equation (1a) describes how the temperature of the wire changes with time: the first term on the right hand side describes the heat flow along the length of the wire; the second term describes heat transfer with the helium bath; and the third term simulates the Joule heating that occurs when the superconductor is in the normal state.

The change in the temperature of the helium bath with respect to time, (1b), is given by a single heat transfer term which acts between the helium and the conductor - there are no terms describing the fluid dynamics of the liquid coolant. This simplification decreases computational complexity but maintains the effect of the helium increasing in temperature and helping to propagate the quench.

We model the specific heat of a nodal superconductor by

\[
C^*_c(T^*(x^*, t^*), T^0_c) = \alpha^* T^*(x^*, t^*)^n \Theta(T^c_c - T^*(x^*, t^*)) + T^*(x^*, t^*)^n \Theta(T^*(x^*, t^*) - T^c_c)
\]

and $\alpha$ and $\gamma$ are material-dependent constants. This model captures the following essential physics (see Fig. 1):

- The specific heat has a linear temperature-dependence above $T_c$ with some fixed Sommerfeld coefficient $\gamma$. This is appropriate for any Fermi liquid at low temperature [13].
- At $T$, the specific heat has a jump, $\Delta C$, as predicted by Landau theory for any second-order phase transition [22]. For simplicity we fix the size of the jump to the value predicted by BCS theory: $\Delta C = 1.43 T_c$ [23].
- Below $T_c$, the specific heat has a power law of temperature characterised by the exponent $n$ which reflects the specific nodal state [12]–[14], as discussed above. The coefficient $\alpha$ is not a free parameter, but is instead fixed by the requirement that the specific heat has the right value at $T_c$. Its dimensionless form is $\alpha^* = 2.43 T_c^{n-1}$.

The simplest case of this model has a constant specific heat with a constant temperature heat bath, however in this case it is easy to show that the specific heat enters only in the timescale $t_0$ of the model, i.e., the specific heat controls the rate of quench propagation and has no effect on whether a quench will happen or not. Introducing a variable specific heat while artificially maintaining a constant temperature heat bath is still not sufficient to model quench behaviour as a cold enough bath will
always prevent a quench, given enough time, no matter the size or intensity of the initial heat pulse. In contrast, the model presented here contained the minimum physics required to simulate a quench. Details of the simpler models are a digression from the main point presented here, hence they have been omitted.

We assume that the system will be kept well below $T_c$ as this is the safest regime to prevent a quench. In this regime a nodal superconductor is preferred as its specific heat rises faster at low temperatures than that of a fully gapped superconductor. More specifically, the nodal superconductor with the lowest exponent will be preferred as it will have the highest specific heat. We can therefore study the effect different topological states can have on quench behaviour by altering the exponent $n$ in (3). In this proof-of-concept work we do not consider the effect of pinning.

III. Method and Results

The model was solved using a forward-in-time centred-in-space (FTCS) algorithm [24] with zero-gradient boundary conditions. The initial temperature profile of the wire has a Gaussian heat pulse centred at the middle of the wire with a temperature peak at $T_0$ and a width $W$ with $T > T_c$, called the hot zone. At the edges of the hot zone are the quench fronts: positions $x_q$ at which $T = T_c$. The quench fronts mark a boundary between the superconducting and normal regions. The time evolution of the wire’s temperature profile is computed using the FTCS algorithm. A quench is said to have occurred once both the entire wire and the helium are above $T_c$. If the full length of the wire goes below $T_c$ then a quench has been prevented.

Fig. 2 shows an example of the wire’s temperature profile evolution during a quench. In this case the initial Gaussian heat pulse expands until the full length of the wire is above $T_c$, at which point it has quenched. The simulation continues until the helium bath is above $T_c$ to ensure that there is no possibility that the wire could cool down again given enough time. In the non-quenching case, the width and height of the initial Gaussian heat pulse decrease until the pulse disappears and the entire wire is below $T_c$.

Time evolution of the quench fronts shows the expansion or contraction of the length of the hot zone, see Fig. 3. If the initial conditions were correct for a quench to occur then the hot zone will increase in temperature and expand; the quench fronts will move outwards until they reach the ends of the wire. If however, the initial conditions were not sufficient for a quench, the quench fronts will move towards the centre of the wire; reducing the length of the hot zone while it decreases in temperature until
In summary, we have asked whether a nodal superconductor could be made more resistant to quenches by tuning its parameters to a node-reconstruction topological transition point. Our calculations, using a minimum model, show that this is indeed the case although the effect is small. This concept has the potential to enhance the quench resilience of superconductors, especially if used in conjunction with current quench detection and mitigation techniques, however, detailed materials modelling will be required to ascertain whether the effect could be useful for applications. Possible candidates include non-centrosymmetric superconductors Li$_2$(Pt, Pd)$_3$B [19] and the high-temperature cobalt-doped pnictides Ba(Fe$_{1−x}$T$_x$)$_2$As$_2$ (T = Co, Ni, Pd) [18], [20], [21] This could lead to the first applications of topological transitions in the fields of energy distribution, storage and magnetic field generation.

REFERENCES


http://link.springer.com/10.1007/3-540-70859-6_3


WHITTESEA et al.: CAN TOPOLOGICAL TRANSITIONS BE EXPLOITED TO ENGINEER INTRINSICALLY QUENCH-RESISTANT WIRES? 0500305


